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STABILITY OF LASER OSCILLATOR SYSTEMS

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One of the goals of the Stanford-University-Nasa-Laser-In-space-Technology Experiment (SUNLITE) program is to develop ultrastable optical frequency oscillators that can lead to high resolution time standards and ultimately standard clocks. During the past year or two there has been remarkable progress towards achieving in the laboratory the fundamental quantum limits for the frequency stability of nonplanar ring oscillator (NPRO) lasers. This work reviews the quantum theoretical limits for laser oscillator stability, compares measured stability levels, and suggests some applications of such ultrastable laser oscillator systems.

If a collimated beam from a light source with a linecenter frequency f_0 is passed through an optical spectrometer (say a prism or high resolution grating), the different frequencies (wavelengths) in the beam would be dispersed about the linecenter f_0 into a band of width Δf. If the bandwidth (linewidth) is very small compared to the linecenter frequency, the linewidth provides a specification of the frequency stability, either in terms of Δf (in Hz) or the unitless ratio $\Delta f/f_0$. In work sponsored by SUNLITE, linewidths for **free running** solid state NPRO lasers with $f_0 = 2.83\text{X}10^{14}$ Hz ($\lambda = 1.06$ µm) were measured at $\Delta f \sim 1$ kHz, which gives a linewidth ratio $\Delta f/f_0 \sim 4\text{X}10^{-12}$. It is useful to compare such measured linewidths with theoretical limits.

The theoretical limit for a free-running laser was first stated by Schawlow and Townes in their prize winning paper in 1958. The Schawlow-Townes linewidth limit can be put in terms of the frequency **noise** (or angular phase jitter) caused by out-of-phase spontaneous emission in the laser oscillator cavity. If S_f (in Hz^2/Hz) is the spectral distribution of frequency noise, the Schawlow-Townes effect causes a constant ("white" in noise parlance) noise distribution $S_{fST} = 2\Delta f_L{}^2 hf_0/P$, where Δf_L is the laser cavity linewidth, h is Plank's constant, and P is the laser output power. The theory states that Δf is related to S_f by $\Delta f = \pi S_f$, which gives a Schawlow-Townes limit of $\Delta f \sim 1$ Hz for the NPRO lasers referred to above. One of the original goals of the SUNLITE program was to achieve the Schawlow-Townes limit with a free-running laser, but that goal has been considerably lowered because of remarkably low linewidths achieved with frequency stabilized (servocontrolled) laser oscillator systems.

Recently linewidths well below the Schawlow-Townes limit (namely, at the millihertz level!) have been achieved at NIST (formerly the Bureau of Standards) using two HeNe gas lasers individually phase-locked to a reference cavity through a servo control loop. The NIST and other work has shown that the theoretical limit to the linewidth for a phase-locked system is related to the frequency noise of the servo feedback loop. In this case, $S_{fFB} = 2\Delta f_R{}^2 hf_0/P$, where Δf_R is the reference cavity linewidth. For one report, $S_{fFB} \sim 10^{-5}$ Hz^2/Hz was observed, and so linewidths $\Delta f \sim 6$ mHz and ratios $\Delta f/f_0 \sim 2\text{X}10^{-17}$ seem feasible. A linewidth ratio at this level would be completely unprecedented! It exceeds the ratio for cesium atomic standards by about 4 orders of magnitude.

For applications in spectroscopy, the linewidth Δf of the light source is very important, because Δf limits the resolution of spectrometers. Moreover, spectroscopy usually involves measurement times τ less than about 1 sec. However, for applications in metrology, measurements involving reference to absolute time and length standards, the stability of the linecenter frequency f_0 is of paramount importance. For this case, the standard measure of oscillator quality is the Allan Variance, $\sigma^2(\tau)$, which gives the variation in the linecenter frequency $f_0(t)$ for measurement times τ that can be much greater than 1 sec. **Linewidth** provides a measure of the short term frequency stability, while **Allan Standard Deviation** ($\sigma(\tau) = \sqrt{\sigma^2(\tau)}$) defines the long term linecenter frequency stability. For many years, Cesium beam and Hydrogen maser clocks have been characterized by $\sigma(\tau)$, in particular, by the "flicker floor" that is usually evident in a graph of $\sigma(\tau)$ for $\tau > 1$ sec. In fact, the flicker floor is used to identify the long term stability of ultrastable oscillators. (In noise parlance, flicker means that $S_f = k/f$, where k = const.) The following table lists $\sigma(\tau)$ flicker floor values for various high quality oscillators.

LONG TERM STABILITY OF VARIOUS OSCILLATORS

Oscillator	Stabilizer	Flicker Floor
HeNe	I_2	1×10^{-12}
CO_2	SF_6	5×10^{-13}
HeNe	CH_4	2×10^{-14}
Cs		1×10^{-14}
H		2×10^{-15}
NPRO	(no long term stabilizer)	4×10^{-13}

For applications that require longer term stability, such as for standard optical oscillators and clocks, a long term stabilizer (Iodine cell or trapped ion) will be included in the NPRO oscillator servo control system. The very narrow short term linewidth will be important for probing very narrow (long lifetime) states of any stabilizer atom. The potential for achieving a flicker floor of 10^{-17} to 10^{-18} seems not unrealistic.

Clock quality oscillators invariably pass into a measurement time domain called "frequency random walk." For Cs beam atomic clocks, random walk frequency changes start for τ values greater than several days. Some Cs clocks have been known to go several weeks or months without a frequency change. Nevertheless, the effects of frequency random walk on a time base can be virtually eliminated by a pairwise intercomparison of clock readings in an ensemble of three or more clocks. The intercomparison (cross correlation) data permit identification of the specific clocks that have suffered from a random walk frequency change. Thus identified frequency changes can be folded into the ensemble average, which permits a very accurate recording of the ensemble time base. At least three clocks are required to identify the specific member of the ensemble that changed frequency.

The actual detection of gravity waves would be the ultimate achievement of an ultrastable laser oscillator clock system. If NPRO laser oscillators can be long term stabilized and space qualified, they could be used on the new space station freedom for applications from time base management to intersatellite communications, and even to detect differences in the dc gravitational potential and eventually gravity waves.

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